INTRODUCTION

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INTRODUCTION TO HIGH INTEGRITY DIE CASTING PROCESSES

1.1 ORIGINS OF HIGH PRESSURE DIE CASTING

Casting processes are among the oldest methods for manufacturing metal goods. In most early casting processes (many of which are still used today), the mold or form used must be destroyed in order to remove the product after solidification. The need for a permanent mold, which could be used to produce components in endless quantities, was the obvious alternative.

In the Middle Ages, craftsmen perfected the use of iron molds in the manufacture of pewterware. Moreover, the first information revolution occurred when Johannes Gutenberg developed a method to manufacture movable type in mass quantities using a permanent metal mold. Over the centuries, the permanent metal mold processes continued to evolve. In the late 19th century processes were developed in which metal was injected into metal dies under pressure to manufacture print type. These developments culminated in the creation of the linotype machine by Ottmar Mergenthaler. However, the use of these casting methods could be applied to manufacture more than type for the printing press.

H. H. Doehler is credited with developing die casting for the production of metal components in high volumes. Shown in Figure 1.1 are diagrams filed with patent 973,483 for his first production die casting machine.[1] Initially, only zinc alloys were used in die casting. Demands for other metals drove the development

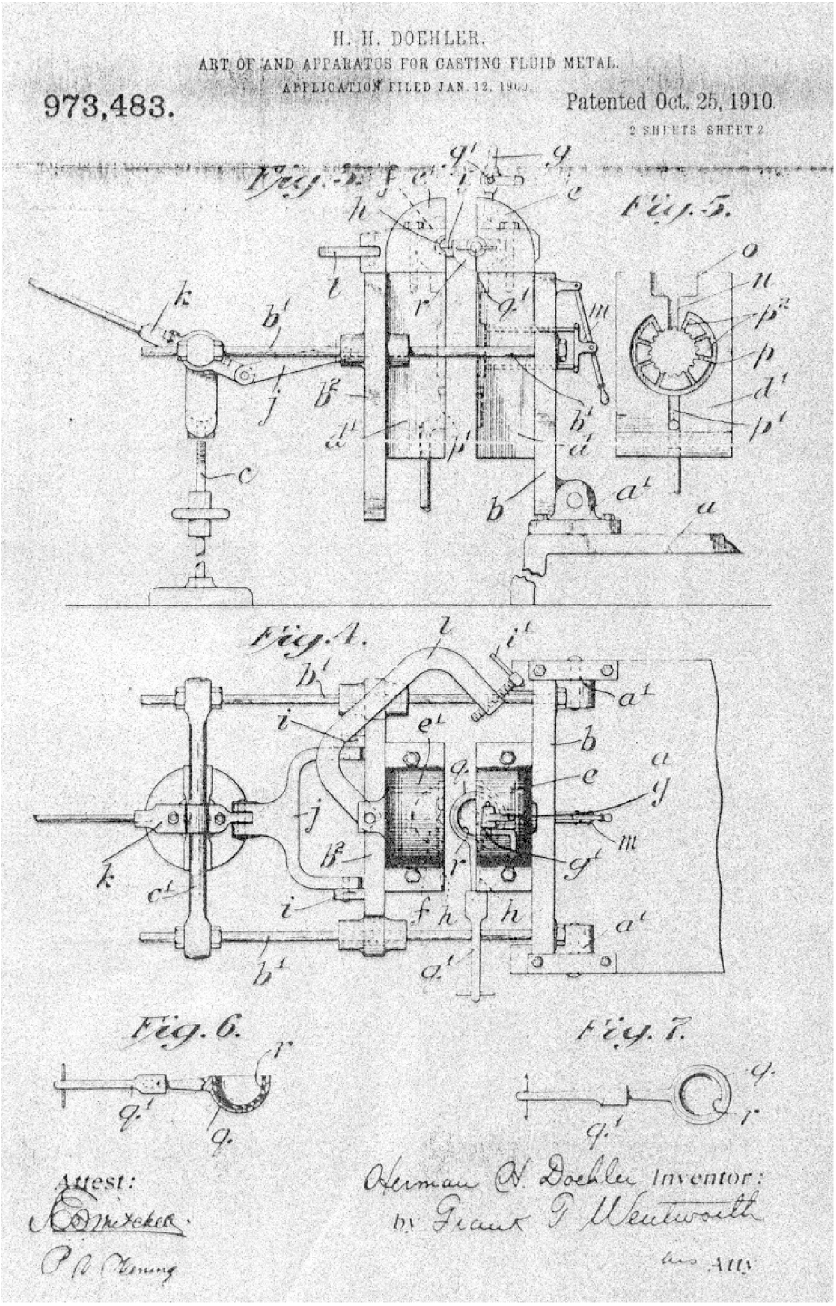

Figure 1.1 Diagrams filed with Doehler's patent for a production die casting machine.

of new die materials and process variants. By 1915, aluminum alloys were being die cast in large quantities.[2]

Much progress has been made in the development of die casting technologies over the last century. Developments continue to be made driving the capabilities of the process to new levels and increasing the integrity of die cast components.

1.2 CONVENTIONAL HIGH PRESSURE DIE CASTING

Conventional die casting (CDC) is a net-shape manufacturing process using a permanent metal die that produces components ranging in weight from a few ounces to nearly 25 kg quickly and economically. Traditionally, die casting is not used to produce large products; past studies, however, have shown that very large products, such as a car door frame or transmission housing, can be produced using die casting technologies.[2] Conventional die cast components can be produced in a wide range of alloy systems, including aluminum, zinc, magnesium, lead, and brass.

Two basic conventional die casting processes exist: the hot-chamber process and the cold-chamber process. These descriptions stem from the design of the metal injection systems utilized.

A schematic of a hot-chamber die casting machine is shown in Figure 1.2. A significant portion of the metal injection system is immersed in the molten metal at all times. This helps keep cycle times to a minimum, as molten metal needs to travel only a very short distance for each cycle. Hot-chamber machines are rapid in operation with cycle times varying from less than 1 sec for small components weighing less than a few grams to 30 sec for castings of several kilograms. Dies are normally filled between 5 and 40 msec. Hot-chamber die casting is traditionally used for low melting point metals, such as lead or zinc alloys. Higher melting point metals, including aluminum alloys, cause rapid degradation of the metal injection system.

Cold-chamber die casting machines are typically used to conventionally die cast components using brass and aluminum alloys. An illustration of a cold-chamber die casting machine is presented in Figure 1.3. Unlike the hot-chamber machine, the metal injection system is only in contact with the molten metal for a short period

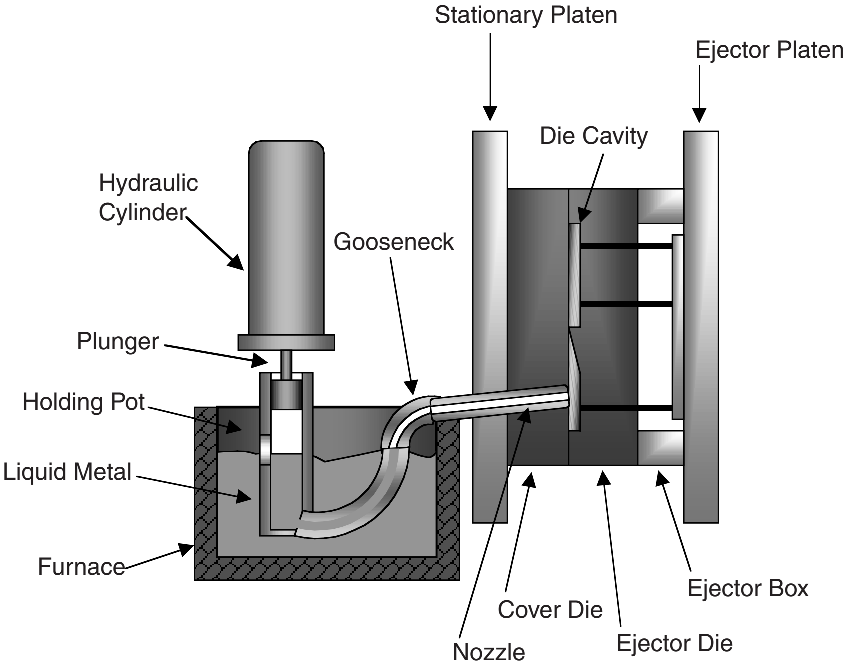

Figure 1.2 Graphical illustration of a hot-chamber die casting machine.

of time. Liquid metal is ladled (or metered by some other method) into the shot sleeve for each cycle. To provide further protection, the die cavity and plunger tip normally are sprayed with an oil or lubricant. This increases die material life and reduces the adhesion of the solidified component.

All die casting processes follow a similar production cycle. Figure 1.4 is an illustration of the cycle using the cold-chamber die casting process as a model. Initially, liquid metal is metered into an injection system (*a*), which is then immediately pushed (*b*) through a runner system (*c*) into a die cavity (*d*) under high pressure. High pressures are maintained on the alloy during solidification. After complete solidification, the die opens (*e*) and the component is ejected (*f*).

Conventional die casting is an efficient and economical process. When used to its maximum potential, a die cast component may replace an assembly composed of a variety of parts produced by various manufacturing processes. Consolidation into a single die casting can significantly reduce cost and labor.

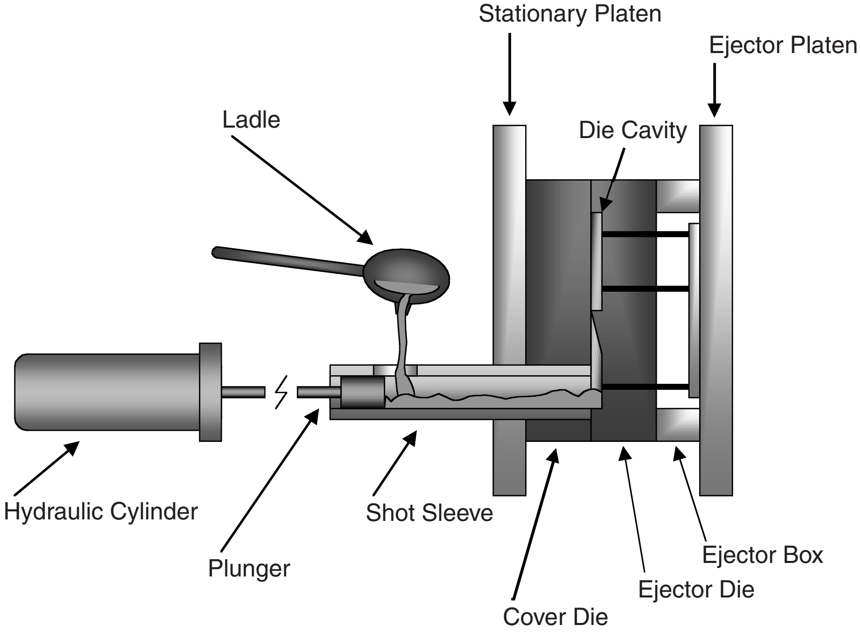

Figure 1.3 Graphical illustration of a cold-chamber die casting machine.

1.3 PROBLEMS WITH CONVENTIONAL DIE CASTING

Conventional die casting is utilized to produce many products in the current global market. Unfortunately, conventional die casting has a major limitation that is preventing its use on a broader scale. A potential defect, commonly found in conventionally die cast components, is porosity.

Porosity often limits the use of the conventional die casting process in favor of products fabricated by other means. Pressure vessels must be leak tight. Conventional die castings often are unable to meet this requirement. Moreover, the detection of porosity is difficult. In some cases, an “as-produced” component is acceptable. Subsequent machining, however, cuts into porosity hidden within the component, compromising the integrity of the product.

Porosity is attributed to two main sources: solidification shrinkage and gas entrapment. Most alloys have a higher density in their solid state as compared to their density in the liquid state. As a result, shrinkage porosity forms during solidification. Due to the

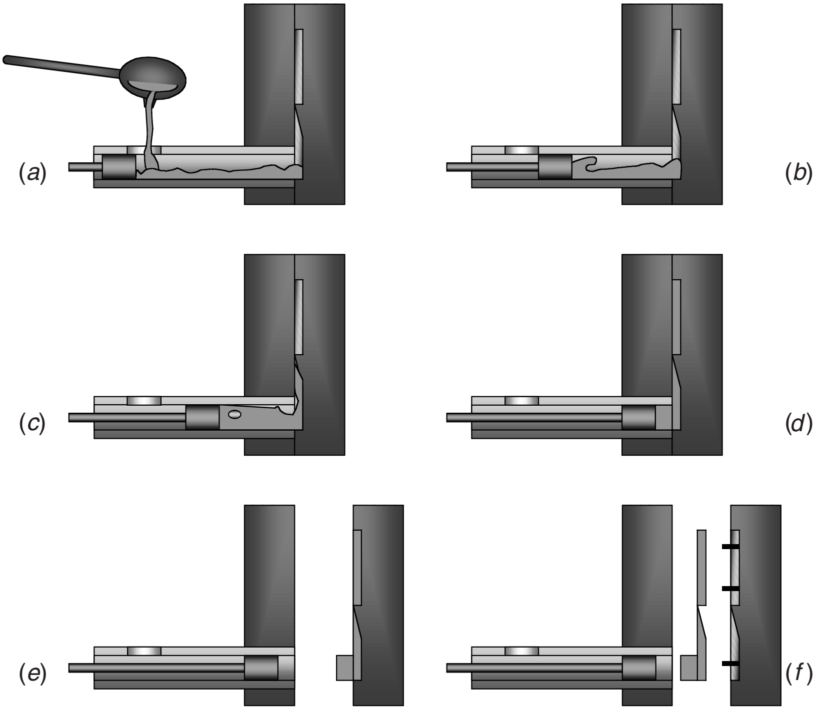

Figure 1.4 Casting cycle for cold-chamber die casting.

turbulent manner in which metal enters and fills the die cavity, gas often becomes entrapped in the metal, resulting in porosity.

Porosity also affects the mechanical properties of conventionally die cast components. In structural applications, porosity can act as a stress concentrator creating an initiation site for cracks.

Numerous studies have documented how porosity in die castings varies with several operating conditions.[3–8] A method has been developed for quantifying the porosity in die cast components.[9] The total porosity contained in a component is defined using the equation

$$\%P = (\text{solidification shrinkage}) + (\text{gas contribution}) \quad (1.1)$$

which can be further defined as

$$\%P = \frac{\beta V^*}{V_c} + \left(\phi \frac{T\,\rho L}{(237\ K)P}\right)(\nu - \nu^*) \tag{1.2}$$

where

$\%P$ = percent porosity,
β = solidification shrinkage factor in percent,
V^* = volume of liquid in casting cavity that is not supplied liquid during solidification in cubic centimeters,
V_c = volume of the casting cavity in cubic centimeters,
T = temperature of the gas in the casting cavity in degrees Kelvin,
P = pressure applied to the gas during solidification in atmospheres,
ϕ = fraction of the gas that does not report to the solidification shrinkage pores,
ρ = liquid alloy density at the melting temperature in grams per cubic centimeter,
ν = quantity of the gas contained in the casting at standard temperature and pressure conditions (273 K at 1 atm) in cubic centimeters per 100 g of alloy, and
ν^* = solubility limit of gas in the solid at the solidus temperature at standard temperature and pressure conditions in cubic centimeters per 100 g of alloy.

The first portion of Equation 1.2 is a relationship for porosity due to solidification shrinkage. The second portion of Equation 1.2 describes the porosity due to gas entrapment. The total gas contained in the casting includes gas from physical entrapment, gas from lubricant decomposition, and gas dissolved in the alloy. This relationship can also be described mathematically,

$$\nu = \nu_{\text{Entrained}} + \nu_{\text{Lube}} + \nu_{\text{Soluble gas}} \tag{1.3}$$

Each of the gas contributions in Equation 1.3 is expressed in cubic centimeters at standard temperature and pressure conditions per 100 g of alloy.

In addition to porosity, the microstructures inherent with the conventional die casting cannot meet the mechanical requirements needed for many applications. Subsequent heat treating, which can alter the microstructure, is rarely possible due to defects that emerge during thermal processing, such as blistering.

Regardless of the limitations found in conventional die cast components, demands exist for high integrity products. In many cases, product engineers and designers turn to investment casting, forging, injection molding, and assembled fabrications to meet necessary requirements. Typically, these processes are more costly than conventional die casting in both processing time and raw material costs.

1.4 STRATEGIES TO IMPROVE DIE CASTING CAPABILITIES

Several efforts have proven successful in stretching the capabilities of conventional die casting while preserving short cycle times and providing dimensional stability and other beneficial characteristics. In these efforts, three strategies have extended the capabilities of the die casting process:

1. eliminating or reducing the amount of entrapped gases,
2. eliminating or reducing the amount of solidification shrinkage, and
3. altering the microstructure of the metal.

The first two strategies noted affect each of the major quantities that contribute to porosity as defined in Equation 1.1. The third strategy addresses the mechanical properties by modifying the fundamental structure of the die cast component.

1.5 HIGH INTEGRITY DIE CASTING PROCESSES

Three high integrity die casting processes have been successfully developed and deployed for commercial use in high volume production. These processes are vacuum die casting, squeeze casting, and semi-solid metalworking (SSM).

Vacuum die casting utilizes a controlled vacuum to extract gases from the die cavities and runner system during metal injection. This process works to minimize the quantities of $\nu_{\mathrm{Entrained}}$ and ν_{Lube} as defined in Equation 1.3. Porosity due to entrapped gases is virtually eliminated.

Squeeze casting is characterized by the use of a large gate area and planar filling of the metal front within the die cavity. As with vacuum die casting, this process works to minimize the quantities of $\nu_{\mathrm{Entrained}}$ and ν_{Lube} as noted in Equation 1.3. The mechanism, however, is much different. Planar filling allows gases to escape from the die, as vents remain open throughout metal injection. Furthermore, the large gate area allows metal intensification pressure to be maintained throughout solidification, reducing the magnitude of V^* as defined in Equation 1.2. Both porosity from entrapped gas and solidification shrinkage are reduced by using squeeze casting.

Semi-solid metalworking is the most complex of the high integrity die casting processes. During semi-solid metalworking a partially liquid–partially solid metal mixture is injected into the die cavity. The fill front is planar, minimizing gas entrapment, as in squeeze casting. Moreover, solidification shrinkage is greatly reduced, as a significant portion of the metal injected into the die cavity is already solid. Semi-solid metalworking addresses both sides of the porosity relationship defined in Equation 1.1.

In addition to reducing porosity, a unique microstructure is generated during semi-solid metalworking. The mechanical properties inherent to this microstructure are superior to those created in conventionally die cast components.

Products produced using high integrity die casting processes have little or no porosity. Moreover, the mechanical properties are much improved in comparison to conventional die cast components. This is due to reduced levels of porosity, the viability of subsequent heat treating, and formation of microstructures not possible with the conventional die casting process.

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